

This part discusses use of the simulator for problems associated with urban traffic studies.

Included are simulation methods for intersections and networks, vehicular characteristics and input, and the network traffic control mechanism.

The general purpose simulator is used to write a general traffic program which is used with data cards specifying the geometry, signal settings, statistical distributions, and other details of the particular network selected for simulation.

A general purpose digital simulator and examples of its application

Part III — Digital simulation of urban traffic

by A. M. Blum

Digital simulation has already been proven effective for urban traffic studies.¹⁻⁴ However, considerable effort is required to program the computer for simulations of any complexity.

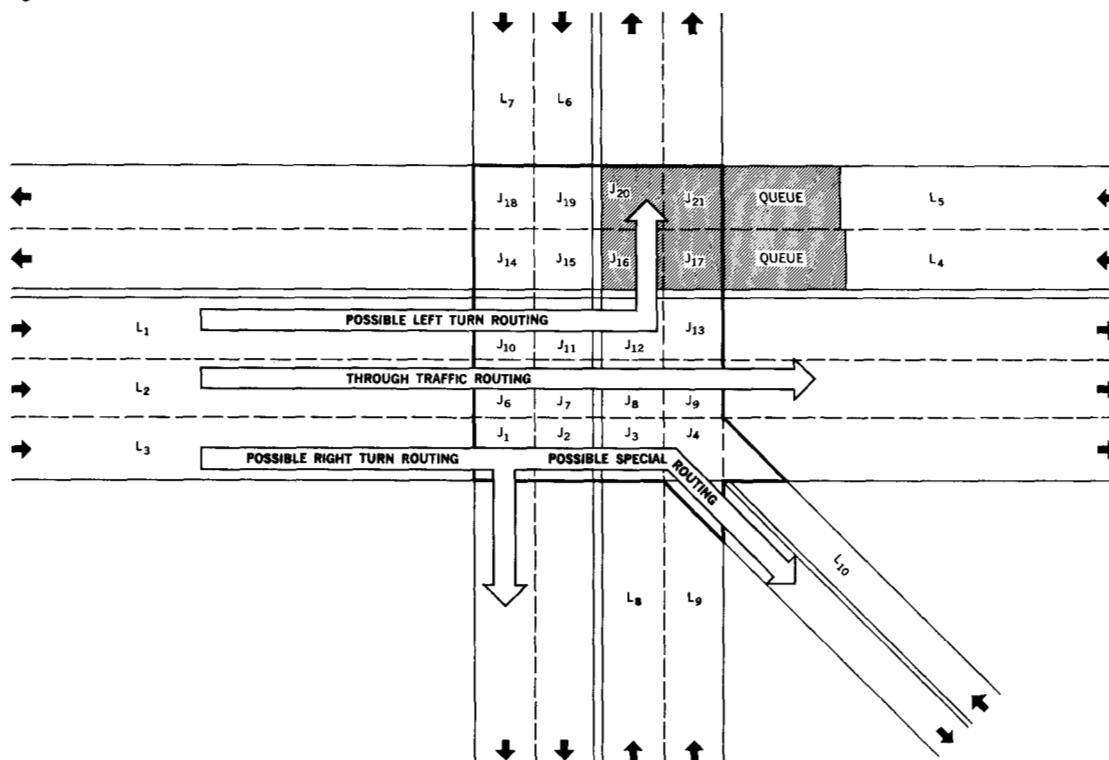
This article suggests how a substantial reduction in the programming effort can be accomplished by using the simulator. First, we discuss intersection modules and the method of combining the modules for simulation of an urban network. Next, the means of simulating vehicular behavior within the network and the technique to incorporate the network traffic control mechanism are examined. Then the procedure for simulating system inputs and the type of results that may be obtained from the simulator are considered. Finally, the over-all characteristics of the computer program are described.

The traffic network is simulated by a collection of *intersection modules*. The nature of the modules is discussed with reference to the intersection shown in Figure 1.

An intersection module describes the geometry of each intersection to be simulated and is the medium through which a traffic network is translated into GPSS II language. Intersection configurations are not limited in the number of lanes or in the direction or dimensions of the lanes. Each module consists of the following elements:

intersection
modules

Figure 1 An intersection module



Junction. The region in each intersection common to all the intersecting arteries, i.e., the area for which approaching vehicles compete with one another, is defined as a junction. In GPSS II, each junction is represented by a storage⁶ having a capacity equal to the maximum number of vehicles that can be accommodated in the region defined by the junction. The heavy border around the center of the intersection module in Figure 1 encloses the region identified by the junction.

Junction cells. Each junction is divided into a "checkerboard" arrangement of junction cells of arbitrary size. The boundaries of each of these cells are determined by the region formed by pairs of intersecting lanes in the junction. The cell is the minimum area that may be occupied by competing vehicles when attempting to cross the intersection. In the model, a logic switch is set when a vehicle enters a cell and is not reset until the entire length of the vehicle has proceeded across the cell. Vehicles may occupy more than one cell. In the figure, each cell is numbered in a designated sequence, shown as J_1 , J_2 , etc., in Figure 1.

Lane segments. The portion of a lane from the end of the preceding junction to the beginning of the next one is defined as a lane segment. These segments are also storages with the capacities equal to the lengths of the lane segments in feet. L_1 , L_2 , etc., denote the different lane segments.

Street segments. A set of contiguous lane segments for traffic streams moving in a single direction is called a street segment. In the figure, L_1 , L_2 , and L_3 comprise one street segment, L_4 and L_5 another. Although no explicit GPSS II entities are identified with street segments, numbers to identify them must be provided for use in the routing functions described below.

Signal light facilities. A pair of signal light facilities is related to each *phase* of traffic. A phase refers to the portion of the total cycle length allotted to those traffic streams that are given the right-of-way simultaneously by a single signal light. Thus, the green and amber time for the traffic streams in lane segments L_1 , L_2 , L_3 , L_4 , and L_5 constitute a phase of traffic. The intersection unit shown in Figure 1 has three traffic phases,⁶ one phase for each pair of directions shown. GPSS II facilities represent red traffic signals.

Left-turn zones. The region of the junction that must be free of all vehicles before a left turn may be attempted is called a left-turn zone. Such a zone consists of all opposing junction cells and all oncoming queues, i.e., the cross-hatched area in the figure is the left-turn zone for traffic moving in an easterly direction. Savex locations are used as indicators to specify the status of the left-turn zones.

The physical composition of most intersections can be described by modules consisting of a combination of elements as described above.

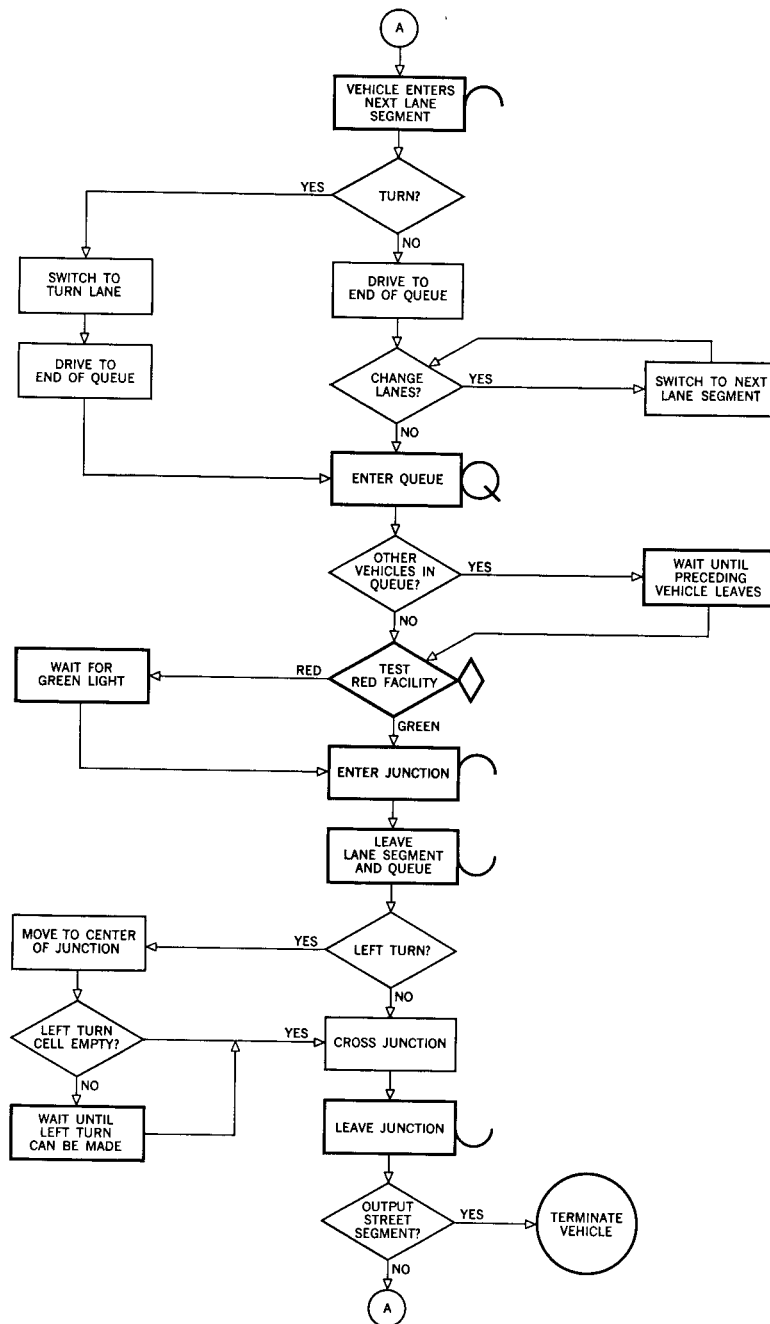
The simulation of a traffic network is achieved by a mapping of all the intersection modules of the area under study and linking them together by properly sequenced lane segments with the data in the form of GPSS II functions.

Internally, the intersection module is reproduced by a single block diagram which processes vehicles (transactions) for the entire network. Figure 2 is a simplified diagram indicating the over-all flow of vehicles between intersection modules. In this diagram, a mixture of conventional and GPSS II blocks appear, with the latter blocks indicated in bold outlines. This same practice of showing only certain key GPSS II blocks is followed throughout the paper. As vehicles move through the block diagram, values (parameters) are assigned to them, referring to the functions which specify street, lane, and junction attributes. These values determine vehicle location and performance as well as vehicle interaction with competing vehicles in the network. Included are such characteristics as vehicle velocity, vehicle length (in feet), signal light number, junction number, routing indicators, queue number (if it exists), lane segment number, etc. Thus, within the intersection module, each vehicle is located in a specific lane segment and/or queue, or in a specific junction region. However, all vehicles are processed with the same set of blocks.⁷

Control over the routing of vehicles across the junction is accomplished by routing functions which specify the paths⁸ to

simulation
of network

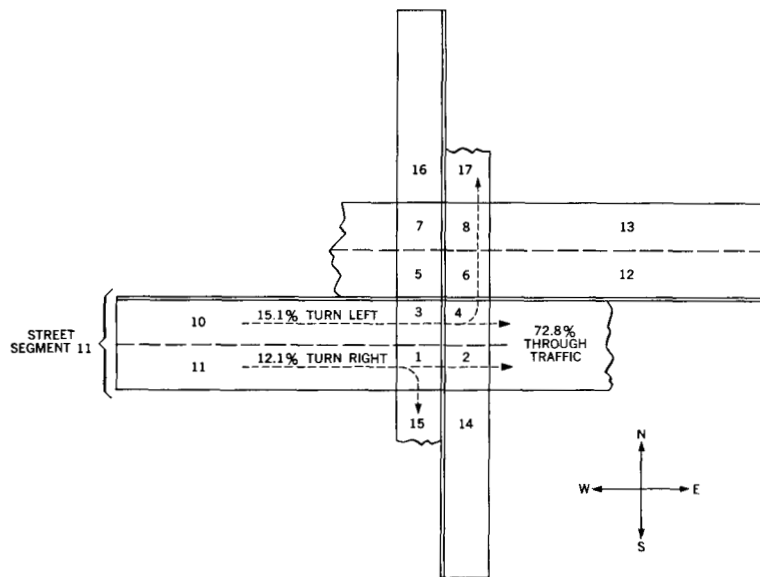
Figure 2 Vehicle flow



be taken by vehicles as they cross the intersection. A route number function locates the street segment of a vehicle and assigns a routing function number to the vehicle according to some known distribution of paths for each street segment.

For example, suppose that, for the intersection shown in Figure 3, the distribution of turns for the street segment number

Figure 3 Intersection



11 in the easterly direction is given by the data in Table 1. The route number function associated with this distribution is shown graphically in Figure 4. The abscissa is a 6-digit number, the low-order three digits denoting the cumulative percentage (given in Table 1) multiplied by ten, the higher-order three digits representing the street segment number 11. The ordinate denotes the routing function number associated with the turn to be effected. When a vehicle enters a new street segment, a random number choice is made. In this example, any number from 0 to 150 results in a left turn, any number from 151 to 878 routes the vehicle straight through the intersection, and numbers 879 through 999 cause a right turn.

Table 1 Turn distribution—
east traffic

Turn	Per- cent	Cumu- lative percent
1 Left	15.1	15.1
2 Through	72.8	87.9
3 Right	12.1	100.0

Figure 4 Route number function

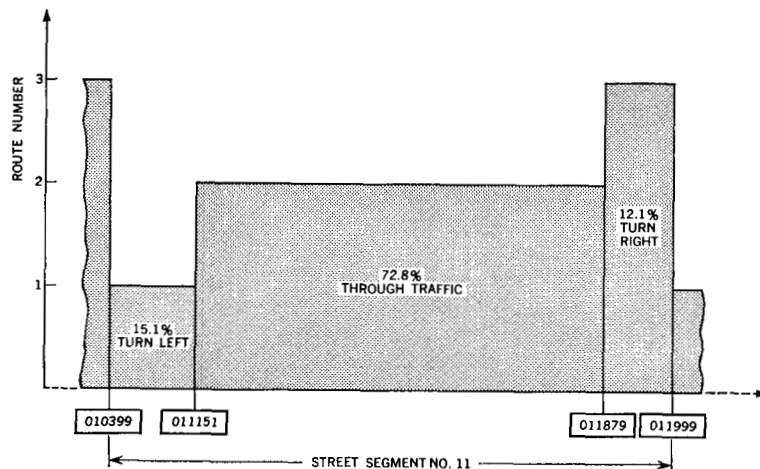


Figure 5 Left-turn routing function

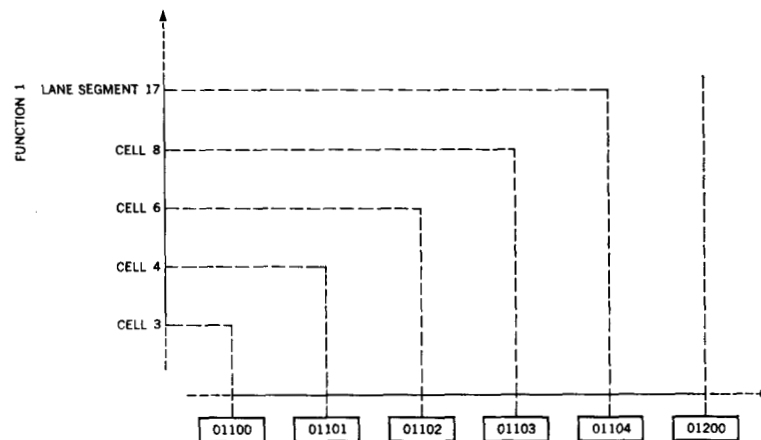


Figure 5 shows the routing function associated with left turns. Here the abscissa, a 5-digit number, is an indexing parameter which is incremented by 1 every time a vehicle enters a new junction cell or lane segment. The two lower-order digits represent the incremented index, the three high-order digits correspond to the street segment number. Hence, all left-turning vehicles are routed over junction cells 3, 4, 6, and 8 into the lane segment number 17. The path could just as well have been over cells 3, 6, and 8 into lane segment 17. The contour of the path is arbitrary, and its choice depends on the traffic laws and practices existing in the area under study. Thus, all left turns can be generated by a single function and, similarly, for any other particular movement (right turn, straight through, etc.).

Similar techniques may be used to guide vehicles on pre-determined paths through the network, making it possible to simulate established traffic flow patterns as well as public conveyances (buses, etc.) and other specially designated traffic.

simulation
of vehicles

Vehicle input areas are located at the peripheral street segments of the network. Special internal sources and sinks of traffic (parking lots, expressway exits, etc.) can also be introduced into the model by specifying them as additional input and output locations.

Interarrival time gaps for vehicles entering the network are generated by negative exponential distributions (based on Poisson arrivals) whose means are determined from empirical data and vary with traffic loads during the day (a.m. rush hour, p.m. rush hour, non-rush hours, etc.). The assumption of Poisson arrivals has been found to be fairly representative both for light traffic and for instances where the effect of a previous signal is negligible. In heavy traffic and/or where a prior signal is of considerable consequence (vehicles usually arrive in platoons at an almost uniform rate), observed distributions may be employed.

A number of operating characteristics are assigned to individual vehicles in the network. Upon entering an intersection, velocity

from an empirical or hypothetical statistical distribution is assigned to the vehicle and retained until the vehicle's free flow is inhibited by a preceding vehicle or signal light. If the vehicle overtakes a preceding one, it either changes lanes or assumes the slower vehicle's speed. A new velocity is assigned to the vehicle when it can move again after its progress has been impeded, i.e., when the road ahead clears, when the vehicle leaves a queue, or when a signal light turns green. Velocity distributions may be applicable to an entire network, or individual street segments may have particular distributions where unusual geographical conditions prevail (hills, ramps, curves, etc.).

Length is assigned to a vehicle when entering the system. Appended to the length, which is taken from a known distribution for the network, is a variable distance to allow for spacing between vehicles. This distance can be treated as a function of velocity and/or density of vehicles (i.e., vehicles per lane segment). When a vehicle enters a lane segment, space in the associated storage is reduced appropriately. The additional spacing displacement (minus some smaller, variable "stopped" distance) is released from storage when a vehicle overtakes another one or comes to a standstill.

Other vehicle parameters may be used to simulate reaction and acceleration time delays. These characteristics can be related to position in queue, velocity, etc.

The traffic in a network is controlled primarily by setting the signal lights. Usually, variation in signal settings include:

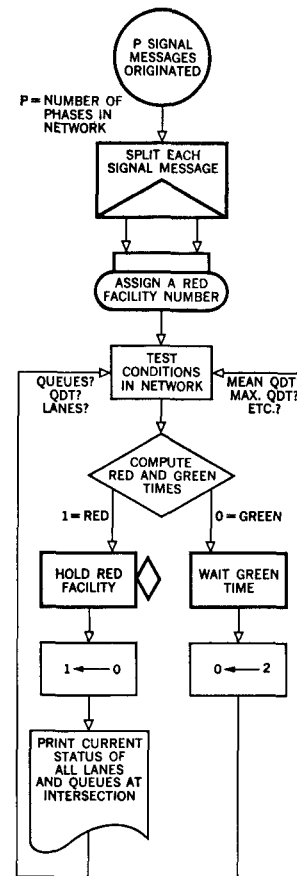
- *Signal cycle length* — total time for a single sequence of red, amber, and green lights.
- *Splits* — percentage of the cycle length for the red and green periods.
- *Offsets* — percentage of cycle length for initial synchronization of consecutive traffic signals to maintain an uninterrupted flow.

Secondary control may be achieved by re-routing traffic, dynamic control of turns, and velocity regulation.

Network control is simulated by a control loop (see Figure 6), an independent block diagram which generates a transaction for each traffic phase at every intersection. The transactions circulate in the control loop, turning the signals on and off at fixed or calculated intervals by holding facilities. Vehicles arriving or waiting at a junction in the intersection module must test a red facility associated with the phase. The junction is not entered or crossed until the facility has been released. The time between seizures of the red facility is the green and amber time for the phase.

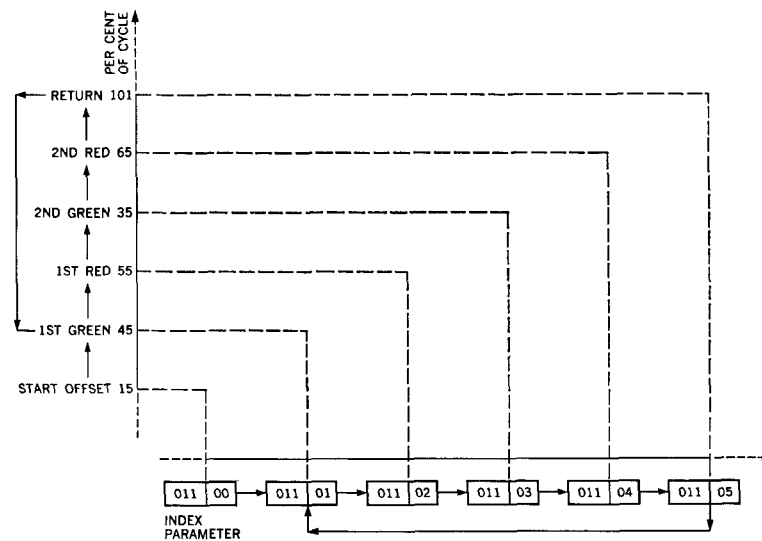
The control loop can operate in two modes: a fixed-signal mode and a real-time adaptive mode. In the fixed mode, signal settings are specified by two functions, one for the signal-cycle length and the other for splits and offsets. The independent variable of the cycle-length function is the number of the traffic phase to which the settings apply. The dependent variable rep-

Figure 6 Control loop



simulation
of network
control

Figure 7 Split and offset function



resents the cycle length itself (in units of 0.01 sec). The format for the split and offset function is similar to that of the routing functions. The independent variable is a 5-digit number, with the two lower-order digits representing an index (now incremented at every light change) and the three high-order digits comprising the phase number. The dependent values give the cycle percentage for offset, green, and red times with the final value (assumed during each phase) coded to indicate that another iteration is to begin. Figure 7 exhibits a split and offset function for phase 11.

At the outset of a simulation run, the control message selects the percentage of offset time and waits the calculated period (proportion of offset time multiplied by cycle length). The index parameter is then incremented by 1, the green split is referenced from the function, and the time is computed as for the offset time. After the green time has elapsed, the index parameter is stepped up once more and the associated red facility is held. This operation continues until the iteration is complete, at which time the loop returns and selects the first green percentage. The offset time is used merely to initiate all signals from the same reference point and is needed only once. The procedure described allows the inclusion of any fixed sequence of settings in the control mechanism of a model.

Since there is little agreement as to the appropriate traffic control algorithm associated with the dynamic real-time mode, illustration is omitted. However, it should be noted that grss 11 has been written with dynamic control problems in mind, so that no difficulty should be encountered in incorporating this type of algorithm within the traffic simulation.

Output from the simulator suitable for computation of standard traffic measures is readily available. For example, the following data may be obtained:

simulator
output

- Distribution⁹ of queue delay times.
- Distribution of queue lengths.
- Distribution of cumulative queue delay times.
- Distribution of cumulative queue lengths.
- Number of vehicles waiting in each queue after each signal change.
- Number of vehicles in each lane segment after each signal change.
- Average utilization of lane capacities.
- Distribution of total travel times for all vehicles.
- Distribution of total travel times for specially routed vehicles.
- Total number of vehicles passing through each intersection.
- Distribution of average speeds.
- Vehicle throughput.
- Network status at specified time intervals.

Most parameters can be referenced from inside the control loop (dynamically). For distributions, however, only the means can be accessed. Dynamic reference permits the parameters to be used as norms for computations included in real-time adaptive control algorithms.

dynamic
control

An experimental program was written and tested on the IBM 7090. The block language diagram for the program required 350 blocks.

computer
program

As in most GPSS II applications, the resulting program is general in character. Details of each particular problem (e.g., geometry of intersections and network, statistical distributions describing vehicular behavior and control) are specified by data cards. The corresponding variation in the number of simulator entities required is suggested by Table 2. In addition, 35 savex locations and 25 logic switches were used. The program contained 50 functions, 75 tables, and 125 variable statements.

Table 2 GPSS II entities required in traffic program

<i>Traffic model entity</i>	<i>Storages</i>	<i>Savexes</i>	<i>Logic switches</i>	<i>Facilities</i>
Lane segments	1	1	2	
Junctions	1			
Left-turn zones		1		
Junction cells			1	
Signal phases				2

The running time of the model varies with the size of the network and the ratios of computer running time to real time were found to range from 1:1 for small networks (10 intersections) to 3.5:1 for larger networks (25 to 50 intersections).

For most applications, the size of the model is limited by the number of vehicles that may be in the network concurrently (an average of 8 core locations are required for each vehicle).

An approximation of vehicle capacity is given by

$$V \approx 3800 - L - (8J + C)/7,$$

where V , L , J , and C denote, respectively, the number of vehicles that can be processed concurrently in the network, the number of lane segments, the number of junctions, and the number of junction cells.

ACKNOWLEDGMENT

The author acknowledges the work of C. J. VanTassel, whose initial traffic model provided the basis for the traffic model described in this paper. G. H. Bean and R. W. Haskell provided valuable assistance in writing several subroutines.

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2. M. C. Stark, "Computer Simulation of Street Traffic," *NBS Technical Note 119*, U. S. Dept. of Commerce, Office of Technical Services, Washington, D. C.
3. S. Y. Rhee, "The Urban Traffic Control Simulator," Thesis as Partial Requirement for Masters Degree, Case Institute of Technology (1962).
4. J. H. Katz, "Simulation of a Traffic Network," *Communications of the ACM* **6**, 8, 480-485 (August 1963).
5. Terms such as *function*, *facility*, *parameter*, *logic switch*, *storage*, etc. are used throughout in the specialized grss II sense defined in Part I of the paper.
6. Disregarding one-way traffic, a phase normally has two opposing directions associated with it. However, situations arise where the signal timings are different for each of these directions. In these cases, one signal light does not control both traffic streams and, hence, a phase exists for each direction.
7. When using grss II, it is normally unnecessary to perform a simulation in iterative cycles of pre-set discrete time intervals. The program maintains a clock, updates time as necessitated by the interaction of the flow diagram with transactions and their concomitant parameters, and scans and schedules events. The clock is updated only when all the events dictated by internal conditions to occur up to a particular time have been processed. Since the time unit can be made as small as desired, discrepancies due to the operation of the model in discrete time intervals are negligible. Selection of 0.01 second as the time unit is for accuracy in internal arithmetical computations rather than for concern over cycle-time variation.
8. A *path* is a list of the numbers of the junction cells occupied by a vehicle during its journey across the intersection. The last number of the list refers to the next lane segment number for directing the vehicle into a new intersection conformation. At this time, the vehicle is recirculated through the intersection module (see Figure 6). In this way, continuity of flow is maintained throughout the network until an output street segment is reached and the vehicle is terminated.
9. Means and standard deviations are supplied with all distribution tables.